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Design and Development of Free Flow Vertical Axis Wind Turbine

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***Abstract* - In this paper the design and development of a free flow vertical axis wind turbine was carried out. The turbines are usually of two categories 1. Horizontal Axis Wind Turbine (HAWT) 2. Vertical Axis Wind Turbines (VAWT) , of these the VAWT has very complicated aerodynamics, hence more emphasis is on development of VAWT as it requires very less space and generates power at a much lower wind speed than the conventional one. The VAWT was developed with the help of Fiber Reinforced Polymer (FRP), Mild Steel and Nylon bushes. The blade profile was selected from the symmetrical profile of NACA. Once the turbine was developed it was tested for its performance at various locations and the results shows that the turbine can generate power at a low wind speed of 5 m/s, which will suit for Indian conditions.**

Keywords- Free Flow Vertical Axis Wind turbine, FRP, NACA, wind speed

I. INTRODUCTION

As the global population increases the need for electrical energy also increases exponentially, hence non-conventional and non-polluting means of producing energy, without affecting the environment has been of greater significance in recent times. In the history of mankind wind energy has played an important role. Among others wind energy was harnessed to grind grain. These so called wind mills are of the Horizontal Axis Design (HAWT) and were also used for pumping water and later for sawing wood etc. Using multiple blades, the wind energy generated by the atmosphere is converted to kinetic energy inside the turbine. As more attention was put on the environmental effects of traditional fossil fuels, the development of wind turbines for generating electricity became more important. In general there are two main categories of wind turbines: Horizontal Axis Wind Turbines (HAWT) and Vertical Axis Wind Turbines (VAWT) (see Figure 2). Vertical Axis Wind Turbines are one of those kind which are more efficient in converting the wind power into kinetic energy thereby running the generator coupled to it to produce electricity based on Faraday’s Law of Electromagnetic Induction. Although HAWT designs are widely used, they possess the disadvantage of being positioned perpendicular to the wind direction. But VAWT's position is independent of wind direction for their operations and this a major advantage. The latter is further divided into two groups: lift driven VAWT and drag driven VAWT. As the maximum possible efficiency of lift driven turbines is larger than drag driven turbines, it has gained more attention. The first turbine of this design was patented in 1931 by G.J.M. Darrieus [1].

Fig 1: HAWT

Fig 2: Lift driven VAWT

A.VAWT BASICS

The concept of VAWT can have differently shaped blades. As the forces of the blades can be large, the ideal blade has a Troposkien (nearly parabolic) shape with which the centrifugal force is translated through the blade to the shaft. This type of blade is mainly used in large turbines and prevents the blade from failing because of too large rotational speeds. A major disadvantage is the decreasing radius near the top and the bottom of the turbine. These parts experience only low rotational speeds and therefore generate almost no power.

Another concept is the H-Darrieus or Musgrove VAWT. The blades are straight and therefore the radius is equal over the total length of the blade, see Figure 2. The power is now generated over the complete length of the blade. In contrast to the Troposkien shape blade extra strength is necessary to cope with the centrifugal forces. The blades can be rotated slightly to disperse the moment forces on the axis over a larger angle. A typical VAWT consists of the following parts**:**

- Supporting mast
- Rotational axis
- Supporting struts for the blades
- Blades
- Generator
- Converter

The blades of a VAWT have to develop lift and must have enough thickness to withstand the loads. To achieve this they have a certain shape, comparable to aircraft wings. This shape determines how the wind energy is converted to forces on the blade. The goal of this study is to develop a new air foil profile for an H-Darrieus vertical axis wind turbine. In most of the existing turbines of this type, standard profiles like the NACA 0015 and NACA 0018 have been used. These profiles were developed in the early 1930’s by the NACA as standard profile series for turbulent flow. Although these air foils have existed for a long time, not much experimental data is available. As the design involves a relatively small turbine, the Reynolds numbers are small. For most existing air foils no data is available for these Reynolds numbers.

II.DESIGN CRITERIA

A. Basic Aerodynamics

As the VAWT has a rotational axis perpendicular to the oncoming airflow, the aerodynamics involved are more complicated than conventional HAWT. The main benefit of this layout is the independence of wind direction. The main disadvantages are the high local angles of attack involved and the wake coming from the blades in the upwind part and from the axis. If the turbine is represented in a two dimensional way (Figure:4) these characteristics are more obvious. The rotational speed can be varied by the turbines controller for a certain wind speed. The rotational speed ω is therefore represented by the tip speed ratio λ. This parameter gives the tip speed R_ω as factor of the free stream velocity V_{inf}.

$$\lambda = \frac{R_\omega}{V_{inf}}$$

The Reynolds number is a measure of the viscous behaviour of air:

$$R_e = \frac{\rho\, v\, c}{\nu}$$

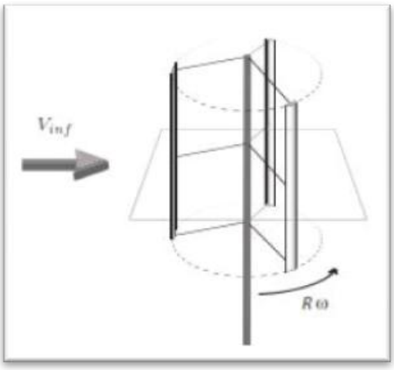

Fig 3 : 3D Schematic View

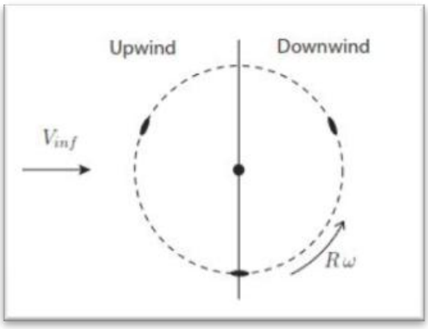

Fig 4: 2D Schematic View

The performance of the turbine is given by the power coefficient C_P. This coefficient represents the produced energy of the turbine as part of the total wind energy passing through the swept area of the turbine. This area equals the frontal area of the turbine given by the height times the diameter. This coefficient is normally plotted against the tip speed ratio λ at a certain Reynolds number. The tip speed ratio and Reynolds number are in this case both dependent of V_{inf}.

B. Flow Conditions

Below are the prevailing flow conditions for a VAWT described. These conditions are important to set the design goals and the correct boundary conditions for the design. The concluding design goals are given in the following section.

1) Angle of Attack

One of the largest challenges of the VAWT is the wide range of angles of attack the blades experiences. When the turbine starts from zero rotational speed, the blades even experience back flow. With increasing rotational speed, the maximum angle of attack decreases. The larger the rotational speed, the smaller the influence of the free stream flow on the local speed W. The blade will be optimized for the Turby VAWT, which operates at a tip speed ratio of 3. The maximum angle of attack in this situation equals 16.5°. The angle varies with the turbine azimuth angle θ. As dynamic and exterior effects can increase this angle, a larger angle of attack has to be taken into account in the design phase. In the interval where the angle of attack is negative, the maximum angle of attack is lower. The blades extract energy from the airflow at the upwind side, resulting in a lower air speed and thus a lower angle of attack at the downwind side.

2) Deep Stall

If the angle of attack over a wing is increased, at some moment the airflow will separate. The separation starts at the trailing edge of the air foil and shifts forward with increasing angle. If the angle is increased further the separation moves forward to the leading edge. This phenomenon is called deep stall. At very low Reynolds numbers separation can occur at the air foils nose right away. If the air foil is in deep stall, this condition will be maintained for some time, even if the angle is decreased again. This will cause a hysteresis loop. This phenomenon has a strong negative influence on the performance of the blade, because in the loop the lift is low and the drag remains high. The angle at which deep stall occurs dependents on the Reynolds number and the nose radius. In the VAWT application of air foils large angles of attack are encountered. At the operating tip speed ratio this phenomenon therefore should be avoided or its influence should be kept as small as possible.

3) Dynamic Stall

Dynamic stall is a phenomenon that occurs at air foils with rapid changing angle of incidence. The resulting effect of this changing angle is a difference, a hysteresis in the lift, drag and moment characteristics between increasing and decreasing angle of incidence. Dynamic stall is characterized by the shedding and passage of a vortex-like disturbance over the low pressure surface of the lifting body. The main parameter of influence is related to the air foil motion and the boundary layer separation. The main fields of research in dynamic stall are helicopter or fighter aircraft application. Some of those methods are modified for wind turbine applications and also research specifically in this field is performed.

The VAWT type wind turbine is especially susceptible to dynamic stall, as the change in angle of incidence is large, especially at low tips speed ratios. As the blades perform a complete circle, the blades in the downstream part of the turbine are influenced by the wake resulting from the upstream blades. A good understanding of dynamic stall and the resulting wake is therefore important. First visualization of the dynamic stall for the VAWT was done by Brochier in 1986 [2]. Using a water channel, visualizations were made with LDV and hydrogen bubbles at a Reynolds number of 10,000 and tip speed ratios varying from 1 to 8 on a VAWT turbine with two NACA 0021 blades. The first vortex is formed at the leading edge of the air foil. A second vortex, turning in the opposite direction, originates from the trailing edge. Together they form the characterizing doublet of two counter rotating vortices, which travels downstream to meet the second blade. This is confirmed by measurements made in a water channel using PIV by Fujisawa and Shibuya, 2001 on a one NACA 0018 blade Darrieus turbine without central column [3]. In this case two pairs of stall vortices are found. The first pair is formed at small blade angles and develops through the wake. The second pair is formed at large blade angles and will follow the blade at the inner side.

As the encountered angles of incidence are larger at lower tip speed ratios, the dynamic stall is more present. The structure of the stall itself is independent of the tip speed ratio. At higher ratios, above 4, the dynamic stall will become of less importance. Although dynamic stall will increase the performance of the turbine, it includes also large disadvantages. It will cause an increase in noise, aero-elastic vibrations and blade fatigue.

Both studies show the strong asymmetry in the flow properties inside the turbine. The blades pass through the wake in only a part of the cycle. In this part they will experience highly turbulent flow.

4)Reynold's Number

A crucial factor for small turbine design is the low Reynolds range (<1 million) in which they operate. Most studies in aerodynamics are performed for aircraft applications in which the Reynolds number lies above 3 million. It is very difficult and often impossible to find the right data for air foils in this low Reynolds number range.For the currently used NACA 0021 profile the maximum lift coefficient and the stall angle of attack drastically decreases with a decreasing Reynolds number. These effects can be noticed for all turbulent NACA symmetric air foils. The difference in maximum lift coefficient between Re = 3 million and Re = 0.3 million can be as much as 60%. The VAWT operates at low Reynolds numbers and high angles of attack, therefore the negative Reynolds number effects on the air foils performance have to be taken into account when working with air foil data of higher Reynolds number. From experiments performed on VAWT by Sheldahl [5] the influence of the Reynolds number is also shown. The chord Reynolds number was changed by altering the rotational speed of the turbine. Also the wind speed was changed to view the performance over the tip speed range.

5) Virtual Camber

Research performed by Migliore [4] shows that the aerodynamic characteristics of an air foil differ between situations of curvilinear flow fields and rectilinear flow fields. Due to the fact that the air foil is rotating the symmetric air foil behaves like an air foil in rectilinear flow with camber and with a virtual angle of incidence. The influence of the curvilinear flow field on the aerodynamic characteristics depends very much on the blade chord to turbine radius ratio $\frac{c}{R}$. If this ratio becomes larger, the influence of curvilinear flow increases as well. Virtual camber causes an upward shift of the lift curve and introduces an aerodynamic moment. Virtual incidence causes the lift curve to shift to the left. The exact impact of these phenomena on the air foil performance in VAWT is not yet established.

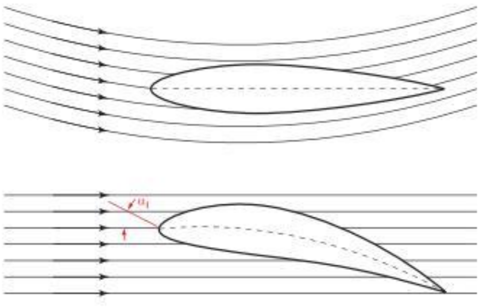

Fig 5: The principal of virtual camber as a result of curvilinear flow [Migliore *et al* ., 1980]

III. FABRICATION OF VAWT

The fabrication of our model was done with the help of FRP, Mild Steel, Nylon, Thrust Bearings and steel box channel for stand. Basic machining processes like turning, drilling, facing were used for developing the desired shape. The Dimensions of the turbine were:

Height: 300 mm Diameter: 200 mm

A. Hub

The hub was developed using a nylon cylinder of 50 mm diameter and 50 mm height. Then the shaft was turned in a lathe to a diameter of 25 mm for 25mm length. The ends were chamfered to avoid sharp edges. Then a circular hole of 12 mm was drilled at the centre of the shaft to accommodate the central shaft.

B. Central Shaft

The central shaft is made up of Mild Steel rod of 12 mm diameter. The height of the rod is 500mm. A small circular hole of 3mm was drilled at the top of the shaft to fix the shaft of the generator used. On the side walls of the main shaft a small hole of 5 mm diameter was drilled to fix a screw thereby coupling the shaft of the generator with the main shaft.

C. Spokes

The spokes are used for connecting the blades to the central shaft. The spokes are made up of mild steel and metal paste with resin is used for attaching the spokes to the blades and circular holes are drilled on the hub for attaching the spokes to the hub. As the spokes are oriented at 120° and are radially pointing upwards the holes in the hub are drilled at the corresponding angle the spokes makes with the hub.

D. BLADES:

The air foil shape used for our turbine is NACA 0021, which is a symmetrical profile. The profile of the air foil is drawn to a chord length of 75 mm. The chord length was decided based on the diameter of the turbine. The chord length should be atleast 40 % of the circumference divided by the number of blades.

Circumference = $2\pi r$ = 2 * 3.14 * 10 = 628 mm
No. of blades = 3
Circumference / No. of blades = 628 /3 = 209 mm 40% 0f 209 mm = 84 mm

Hence we have chosen the chord length of 75mm. First the helical profile was formed on the outer surface of 200 mm diameter pipe, then a template of the shape of the air foil used was made. By using this template the profile was built using FRP. The FRP was arranged in layers sandwiched between resins.

Fig 6: Fabricated VAWT

IV.TESTING

Testing the turbine was the important part of this work. The tests were carried out in different locations like Marakanam,a village in Vilupuram district, TN, Roof top of our college premises, a travelling bus. We also attempted a testing of our turbine in water. The water testing was carried out at Center for Water Resources, Anna University, Chennai under the guidance of Prof. Dr.B.V.Mudgal to analyze its versatility in water flow. The purpose of testing the turbine in various places was to vary to wind speed and to determine the efficiency of the turbine. In order to know the speed of the wind in which we are testing the turbine we used an anemometer.

V.RESULTS AND DISCUSSION

The testing of the turbine revealed that the turbine output increased as the wind speed increased. The results of the test were tabulated and the following graph was obtained.

Table 1: Results of Testing

S.No	**Location of testing**	**Measured wind/water speed (m/s)**	**Turbine output (V)**
1.	Marakanam	8.49	21.3
2.	Roof top	5.83	16.5
3.	Travelling bus	12.5	25
4.	Water testing	3	11

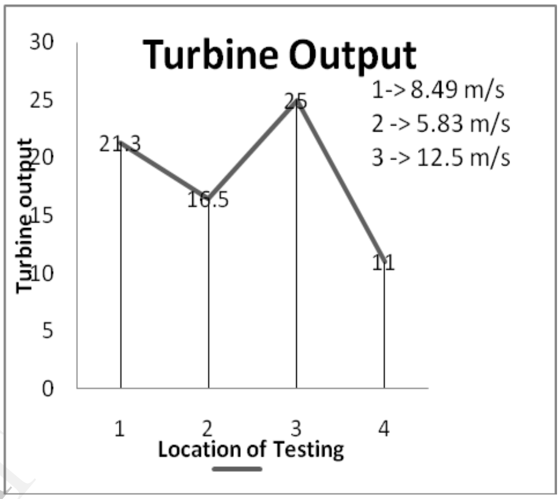

Fig 7: Turbine Output

VI. CONCLUSION

The results of tests conducted on our VAWT at different conditions reinstated that the VAWT rotor is a high speed device of greater efficiency compared to horizontal axis wind turbines. It seems likely that this device will find use in the conversion of wind energy to electric power especially if used on a large scale in conjunction with the grid. In fact a 200 kW turbine driving a generator is currently being tested in Canada. With such large devices it is quite feasible to have adequate control systems for starting and controlling the operation. In India, the mean wind speeds are high during certain period of time and at such times it would be feasible to economically convert wind energy to electric power for grid augmentation. And at times when the wind speed is found to be low, the practical use for wind power is likely to do direct water pumping for drinking water and minor irrigation purposes. The water pumping application generally implies high starting torque and low control costs. Hence it appears, at least from our testing experience, that VAWT turbines are likely to be of much use in the Indian context.

VII. SCOPE OF RESEARCH

This paper deals with only the preliminary testing aspects of our model and based on the upcoming tests, further improvements to improve the operational efficiency will be incorporated and a larger model will be developed.

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